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Sound Channels in the Atmosphere

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Abstract. The mean temperature profile of the atmosphere indicates the probable existence of two horizontally distributed sound waveguides in the atmosphere. The lower one usually occurs between the surface and 50 km, and the upper between 50 and 110 km. Wind data above 30 km, which have become available recently through the use of meteorological rockets, have resulted in revised concepts of atmospheric circulation patterns for the northern hemisphere. Wind data obtained from these patterns have been combined with mean atmospheric temperature data to determine seasonal sonic patterns of the atmospheric waveguide that can exist between the surface and an altitude of about 50 km. These patterns indicate the general existence of a waveguide for sound having an eastward propagation component in winter and a westward propagation component in summer. For other combinations of propagation directions and seasons, a waveguide does not usually exist between the surface and 50 km. The refraction of sound from upper altitudes to the surface will generally occur only in winter at sites located to the east of the source and in summer at sites located to the west of the source.

Introduction. Since the early 1900's, sound (from gunfire or explosion) has been detected beyond a zone of silence surrounding the area in which the sound is normally heard. *Whipple* [1923] first suggested that the reason for this anomalous propagation was the relatively high air temperature in the stratosphere. Since that time numerous studies have verified Whipple's hypothesis [*Cox et al.*, 1949; *Crary*, 1950; *Kennedy and Brogan*, 1945; *Nordberg and Stroud*, 1961].

Sound in the atmosphere may result either from natural causes (earthquakes, volcanoes, thunderstorms) or from man-made noises (explosions, supersonic objects). Theoretical and experimental studies have shown that sound may propagate over long horizontal distances through the natural waveguides that generally exist in the atmosphere between the surface and about 50 km and between 50 and about 110 km [*Brekhovskikh*, 1961; *Dean*, 1959; *Gutenberg*, 1951]. This propagation may occur only if the sound frequencies are sufficiently low to decrease significantly the absorption due to the long mean free path of molecules at high altitudes [*Schrödinger*, 1917]. In this paper the study of sonic patterns will be limited to the waveguide between the surface and 50 km because of the lack of meteorological data in the higher waveguide. It should be recognized that the existence of high temperatures at altitudes above 12 km may result in the refraction of sound at those altitudes if the frequencies are sufficiently low to avoid absorption.

An example of the sonic profile of the waveguide between the surface and 50 km as determined from the temperature distribution of the 1959 model atmosphere is shown in Figure 1 [*Handbook of Geophysics*, 1960]. It indicates minimum values for the speed of sound between the altitudes of 10 to 25 km, with increasing speeds of sound above and below these altitudes.

Since the air in the atmosphere is constantly in motion, the speed of sound at any point is a function not only of temperature but of direction of sound propagation and the motion of the medium. The incorporation of the latter two parameters in determining the speed of sound may result in a sonic profile that is radically different from that based on temperature only. Various speed-of-sound profiles for different locations, seasons, and directions of sound propagation are shown by *Webb and Jenkins* [1961]. It is the purpose of this paper to present the mean seasonal sonic patterns of the waveguide that usually exists between the surface and an altitude of about 50 km in the northern hemisphere. The determination of these patterns is based upon direction of propagation, mean winter and summer temperatures, and the general

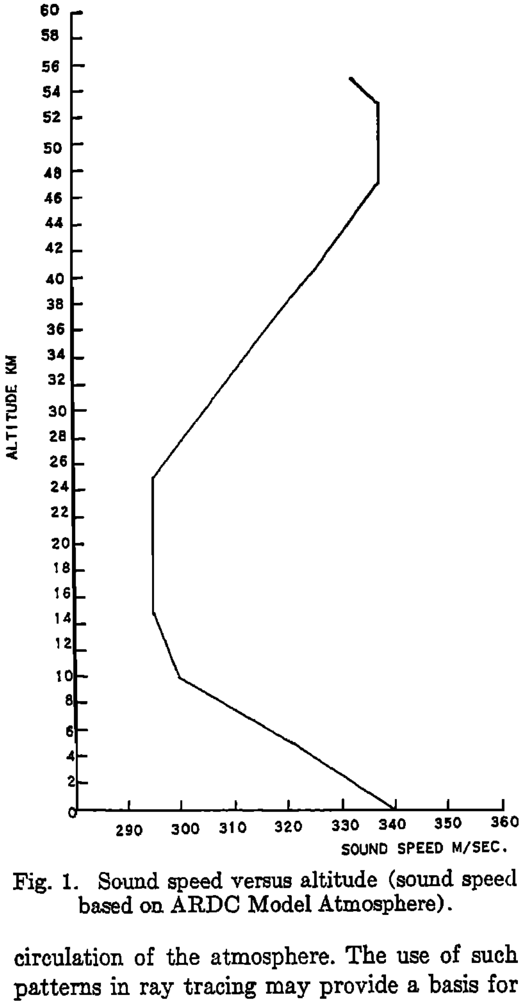

Fig. 1. Sound speed versus altitude (sound speed based on ARDC Model Atmosphere).

circulation of the atmosphere. The use of such patterns in ray tracing may provide a basis for determining surface geographic areas which may be subjected to refracted sound waves. The scattering of sound by atmospheric inhomogeneities and leakage through the atmospheric waveguide by lateral waves may result also in sound arriving at surface areas not normally predicted by ray geometry [*Calvert,* 1961].

Discussion. Sound waves which originate in the atmospheric waveguide may be refracted at about 50 km toward the earth's surface and either reflected from the surface or refracted from some level near the surface. Sound waves refracted from 50 km will reach the surface only if the speed of sound at that level exceeds the speed of sound within any lower layer. If the speed of sound at 50 km is less than that at the surface, the refracted sound will not reach the surface but will be refracted upward from some altitude above the surface at which the sound is equal to the maximum speed of sound at the higher altitude.

The speed of sound (m/sec) in dry, motionless air may be determined approximately from [*Hardy et al.,* 1942]

$$C = 20.1 \sqrt{T}$$

where T is absolute temperature in °K. With a fixed coordinate system, the speed of sound in a moving medium may be determined approximately from

$$C = 20.1 \sqrt{T} + u \cos \theta$$

where u is wind velocity (m/sec) and θ is the angle between direction of propagation and direction of wind.

The speed of sound in the lower atmospheric sound channel is primarily a function of the air temperature, since the effect of wind usually changes the speed of sound by less than 10 per cent. The effect of vertical variation of air temperature, wind velocity, and wind direction on sound propagating in opposite directions is shown in Figure 2. No sound channel exists for the sound traveling from east to west. Geographic areas to the west of the source would not be exposed to any sound waves refracted from altitudes near 50 km, but areas to the east of the source might receive refracted sound waves.

In recent years, through the use of meteorological rockets, wind data have become available for altitudes above 30 km. *Batten* [1961] has used these data to construct a new zonal cross section of the atmosphere between the surface and 100 km in the northern hemisphere. Wind data obtained from these new zonal cross sections and mean temperatures from the *Handbook of Geophysics* [1960] were used in computing the speed of sound at 5-km intervals between the surface and 50 km for northern hemisphere latitudes of 15°, 25°, 35°, 45°, 55°, 65°, and 70°. At each level and latitude the speed of sound was computed for sound propagating along any 10° axis between 0° and 360° for both winter and summer.

Results. The mean sonic patterns of the atmospheric waveguide between the surface and 50 km for sound propagating eastward and westward during both winter and summer are shown in Figures 3 and 4.

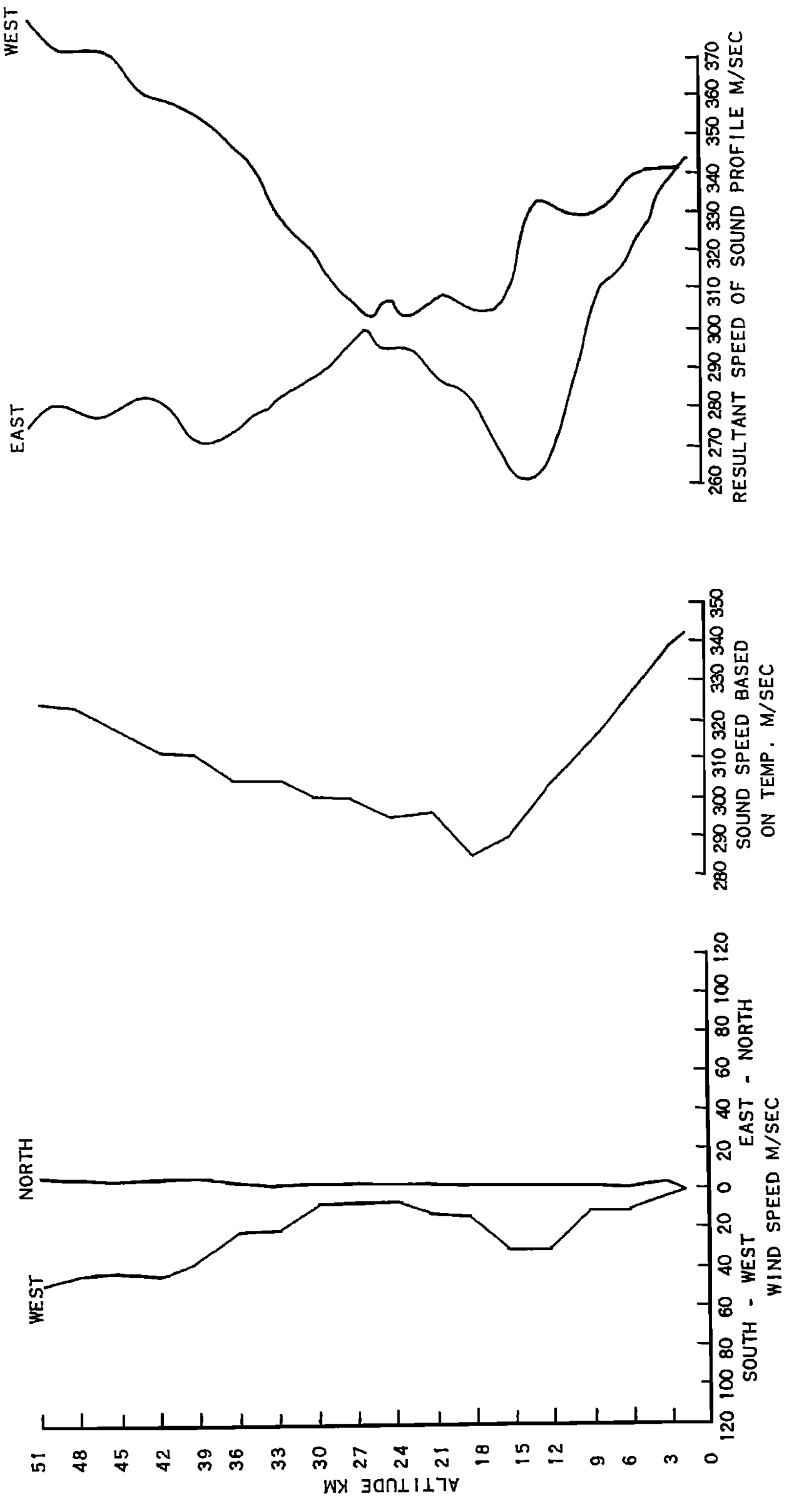

Fig. 2. Wind and speed-of-sound profiles at White Sands Missile Range, New Mexico.

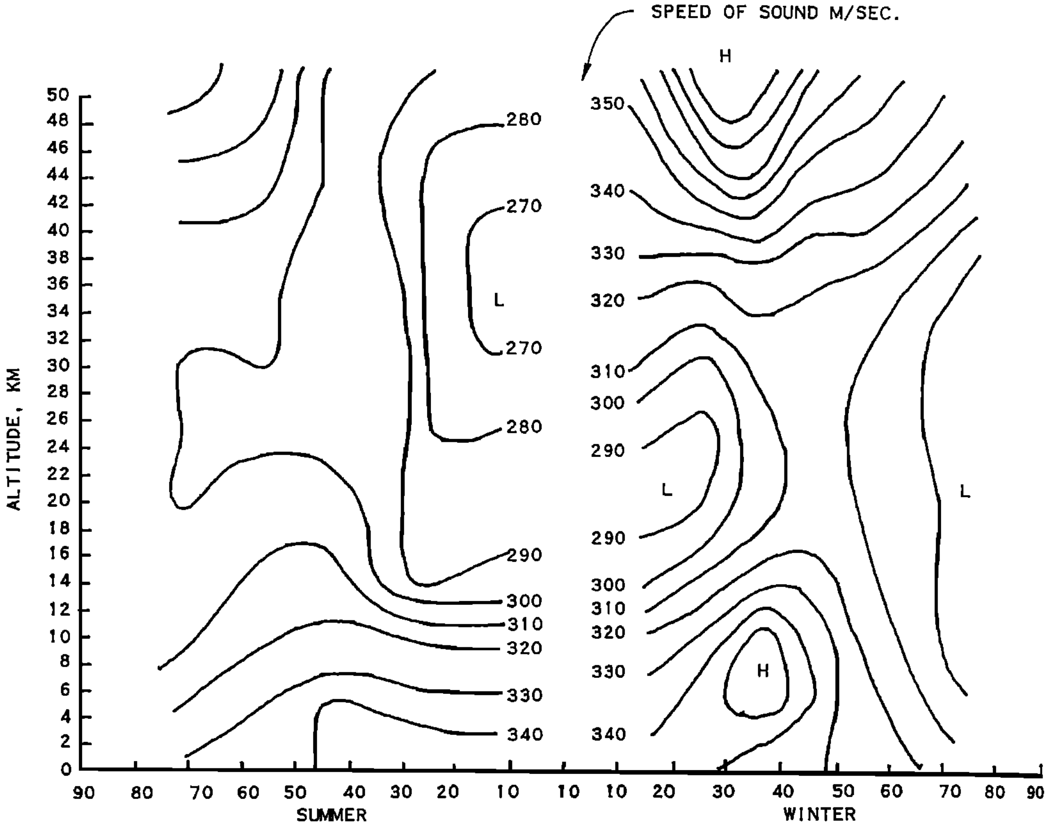

Fig. 3. General sonic structure of atmosphere for sound propagating from west to east.

The sonic pattern for sound propagating eastward during the winter as shown in Figure 3 indicates at all latitudes high values of speed at both 50 km and the surface, with low values at about 22 km. The speed-of-sound values at 50 km are generally much higher than those at the surface, indicating that sound refracted from that level or below would reach the surface. This is especially true of the areas between 25° and 35° of latitude, where the speed of sound at 50 km is much higher than the surface speed of sound.

The pattern for sound propagating eastward during the summer shows a large area of low-speed values at higher altitudes south of 55° latitude, indicating that little refracted sound from 50 km or less would reach the surface. A detailed inspection of this pattern shows that only at about 70°N might refracted sound reach the surface.

The sonic pattern for sound propagating westward during the summer as shown in Figure 4 is similar to that for sound propagating eastward during the winter (Figure 3) in that there are high-speed values at both 50 km and the surface and low-speed values in between. During the winter, the sonic pattern of westward-propagating sound shows low-speed values at almost all altitudes above 12 km, with little possibility of refracted sound reaching the surface.

The zonal cross sections derived by *Batten* [1961] indicate a zone of light winds at about 20 km during both winter and summer, with much stronger winds above and below this altitude. This generally results in high speed-of-sound values for sound propagating in the direction of prevailing wind flow, which is usually westerly in winter and easterly in summer. One exception is the weak westerly flow below 20 km during the summer.

The altitude of minimum sonic speed value is about 5 km lower for westward-propagating sound during the summer than eastward-propagating sound during the winter.

Since sound refracted from the upper atmo-

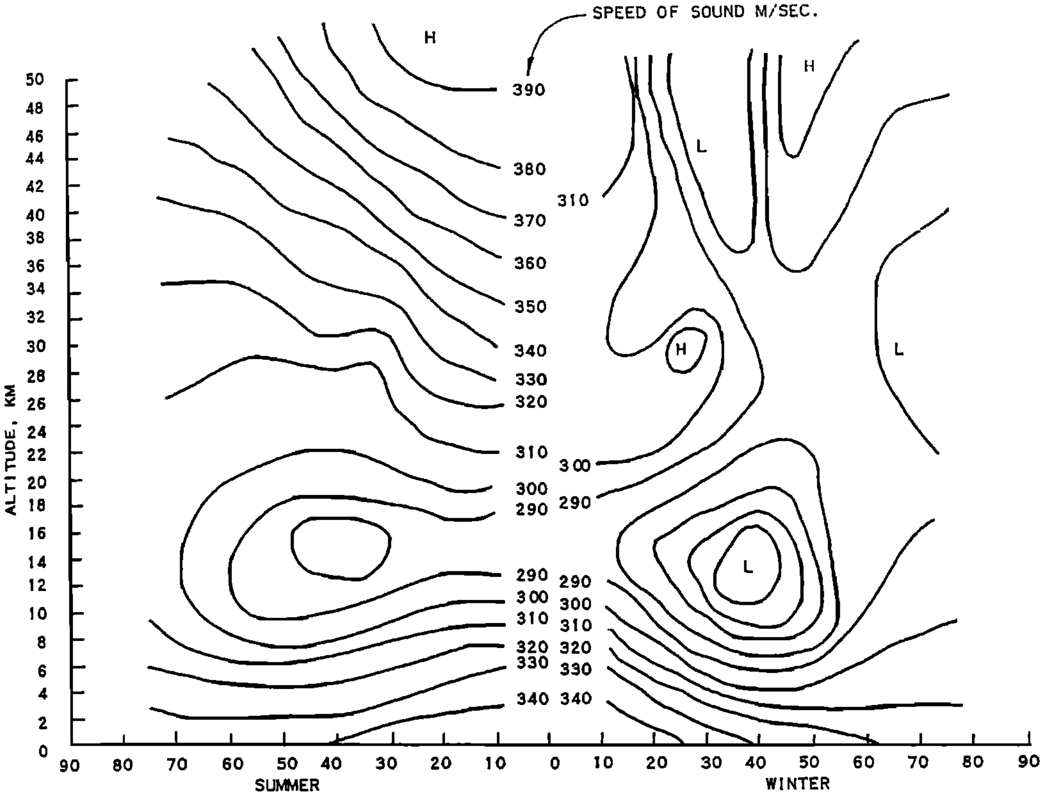

Fig. 4. General sonic structure of atmosphere for sound propagating from east to west.

sphere can reach the surface only if the speed of sound at the surface is less than that at the higher altitudes, the sonic profile can be used to estimate the occurrence of refracted sound at the surface. Also, since the shape of the sonic profile is a function of the direction of sound propagation, the sonic profile can be used to estimate the azimuths from which propagating sound can be expected to be refracted from the upper levels and to return again to the surface. This has been estimated from the previously computed sonic profiles. The results (Figure 5) indicate that whereas in general, during the winter, sound propagating eastward will be received at a site on the earth's surface only if the source is located along an azimuth of 180° to 360° from the site, stations at latitudes between 25° and 45° north will not receive sound if the source is located along an azimuth between 210° and 330° from the station.

During the summer, sound propagating westward will in general be received at a site on the earth's surface if the source is located along an azimuth between 0° and 180° from the site. The vertical distribution of wind and temperature appears to be such that surface sites at 70° latitude may receive refracted sound from any azimuth.

Conclusions. The sound waveguide which occurs normally in the atmosphere between the surface and 50 km exists only seasonally for specific directions of propagation. Seasonal changes in the general circulation of the atmosphere as deduced from newly acquired wind data above 30 km can result in either an intensification or elimination of the waveguide, depending upon the direction of propagation. In general, it appears that eastward-moving sound will be refracted to the earth's surface only during the winter, and westward-moving sound will be refracted to the earth's surface only during the summer. The pattern of the sound waveguide exhibits minimum speed values in the vicinity of 15 km for westward-moving sound, and 22 km

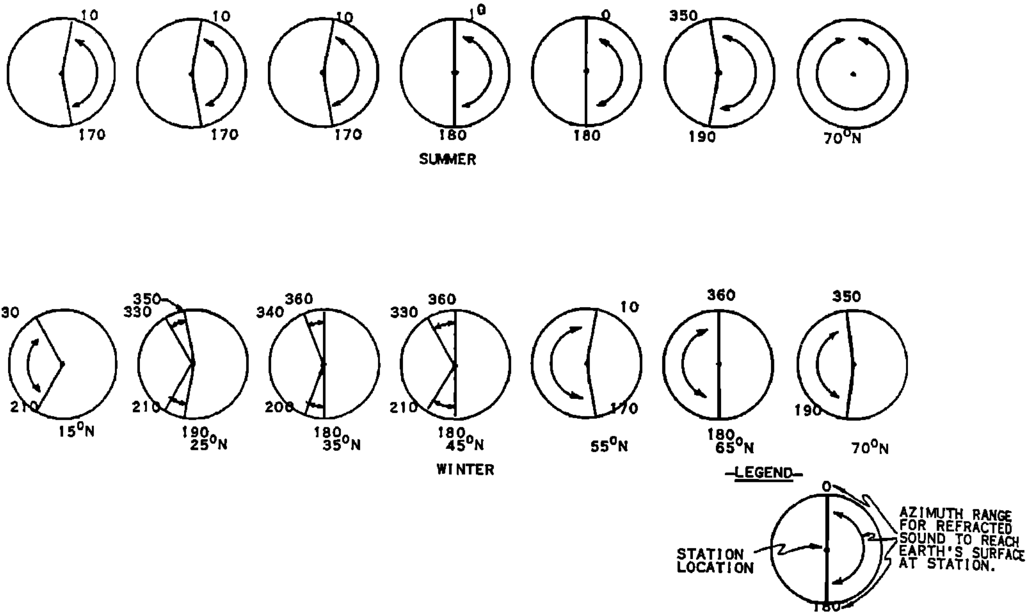

Fig. 5. Azimuth range of sound reaching the earth's surface as a function of season and latitude.

for eastward-moving sound. Although future data may alter the details of the sonic patterns presented, it is believed that the general results will probably remain unchanged. The acquisition of wind and temperature data up to 130 km will permit a similar study to be made of the upper waveguide and the interaction between waveguides in the propagation of sound.

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